

FSU-HEP-950301
 UR-1411
 ER-40685-858
 UH-511-826-95

SUPERSYMMETRY REACH OF AN UPGRADED TEVATRON COLLIDER

Howard Baer¹, Chih-hao Chen¹, Chung Kao² and Xerxes Tata³

¹*Department of Physics, Florida State University, Tallahassee, FL 32306, U.S.A.*

²*Department of Physics and Astronomy, University of Rochester, Rochester, NY 14627, U.S.A.*

³*Department of Physics and Astronomy, University of Hawaii, Honolulu, HI 96822, U.S.A*

(February 1, 2008)

Abstract

We examine the capability of a $\sqrt{s} = 2$ TeV Tevatron $p\bar{p}$ collider to discover supersymmetry, given a luminosity upgrade to amass 25 fb^{-1} of data. We compare with the corresponding reach of the Tevatron Main Injector (1 fb^{-1} of data). Working within the framework of minimal supergravity with gauge coupling unification and radiative electroweak symmetry breaking, we first calculate the regions of parameter space accessible via the clean trilepton signal from $\widetilde{W}_1 \widetilde{Z}_2 \rightarrow 3\ell + \cancel{E}_T$ production, with detailed event generation of both signal and major physics backgrounds. The trilepton signal can allow equivalent gluino masses of up to $m_{\tilde{g}} \sim 600 - 700$ GeV to be probed if m_0 is small. If m_0 is large, then $m_{\tilde{g}} \sim 500$ GeV can be probed for $\mu < 0$; however, for $\mu > 0$ and large values of m_0 , the rate for $\widetilde{Z}_2 \rightarrow \widetilde{Z}_1 \ell \bar{\ell}$ is suppressed by interference effects, and there is *no* reach in this channel. We also examine regions where the signal from $\widetilde{W}_1 \overline{\widetilde{W}_1} \rightarrow \ell \bar{\ell} + \cancel{E}_T$ is detectable. Although this signal is background limited, it is observable in some regions where the clean trilepton signal is too small. Finally, the signal $\widetilde{W}_1 \widetilde{Z}_2 \rightarrow \text{jets} + \ell \bar{\ell} + \cancel{E}_T$ can confirm the clean trilepton signal in a substantial subset of the parameter space where the trilepton signal can be seen. We note that although the clean trilepton signal may allow Tevatron experiments to identify signals in regions of parameter space beyond the reach of LEP II, the dilepton channels generally probe much the same region as LEP II.

I. INTRODUCTION

The search for weak scale supersymmetric particles is a high priority item for colliding beam experiments [1,2]. Supersymmetric models with sparticles of mass $\sim 100 - 1000$ GeV are known to stabilize the Higgs boson mass against quantum corrections which tend to escalate m_H to some ultra-high mass scale when the Standard Model (SM) is embedded within a larger framework. Furthermore, weak scale supersymmetry (SUSY) allows for a simple unification of gauge coupling constants at a unification scale $M_U \sim 2 \times 10^{16}$ GeV [3]. So far, no direct evidence for supersymmetry has been found either at LEP [4] (where sparticle mass limits of $\sim \frac{M_Z}{2}$ have been obtained), or at Tevatron experiments (which have excluded gluinos and squarks lighter than about 150 GeV [5]).

In the future, LEP II is expected to explore sparticle masses up to m_{H_ℓ} , $m_{\tilde{W}_1}$, $m_{\tilde{t}_1}$, $m_{\tilde{\ell}} \sim 90$ GeV [6,2]. The Fermilab Tevatron experiments will be able to explore further ranges of $m_{\tilde{g}}$ and $m_{\tilde{q}}$ by searching for multi-jet+ E_T events and multi-lepton + multi-jet + E_T events from gluino and squark cascade decays [7]. Even if gluinos and most of the squarks are beyond the reach of Tevatron collider experiments, it may still be possible to find signals for the top squark [8], which is expected [9] to have a mass lighter than, and sometimes much lighter than, the other five flavors of squarks.

There has recently been much interest in the clean trilepton signal from $\widetilde{W}_1 \widetilde{Z}_2 \rightarrow 3\ell$ at the Tevatron collider [10–19]. Many studies within the minimal supergravity (SUGRA) framework, find that $m_{\widetilde{W}_1} \simeq m_{\widetilde{Z}_2} \sim (\frac{1}{4} - \frac{1}{3})m_{\tilde{g}}$; it may thus be that gluinos and squarks are beyond the reach of Tevatron experiments, while charginos and neutralinos are produced with significant cross sections. In addition, the \widetilde{Z}_2 (and sometimes also the \widetilde{W}_1) frequently have large branching fractions to leptons. This is in part because slepton masses are typically smaller than squark masses, so that decays via virtual sleptons are enhanced. Also, in some regions of parameter space, sparticle mass and mixing patterns and/or interference effects can enhance (but also diminish) the leptonic branching fraction of \widetilde{Z}_2 , even if $m_{\tilde{\ell}} \sim m_{\tilde{q}}$. Combining production cross sections with branching ratios shows that the clean $3\ell + E_T$ signal can be substantial over large regions of parameter space, whereas SM backgrounds for this topology are expected to be tiny.

Already the CDF and D0 experiments at the Tevatron collider have collectively accumulated an integrated luminosity in excess of $0.1 fb^{-1}$ and should amass a considerably larger data sample by the end of the current run, run IB. This should allow an exploration of $m_{\tilde{g}} \sim 200$ GeV ($m_{\tilde{g}} \sim 250$ GeV) for $m_{\tilde{q}} \gg m_{\tilde{g}}$ ($m_{\tilde{q}} \sim m_{\tilde{g}}$), via the multi-jet+ E_T search [2]. In addition, experiments will finally be sensitive to exploring some of parameter space via top squark searches, and via clean trilepton searches. The Tevatron Main Injector (MI) is expected to begin operation in 1999, at $\sqrt{s} = 2$ TeV, and should allow for integrated luminosities of $\sim 1 fb^{-1}$ to be accumulated per experiment. Recently, there have been discussions concerning further luminosity upgrades beyond the MI, via anti-proton recycling and storage. These further luminosity upgrades, dubbed the TeV* (TeV-star) project, could possibly accumulate $\sim 25 fb^{-1}$ of integrated luminosity per experiment. In this paper, we evaluate the capability of the MI and TeV* to search for sparticles, and compare their reach with that of LEP II and the recently approved LHC.

We work within the framework of the minimal SUGRA model [20] with radiative breaking of electroweak symmetry. Several groups [21] have studied the expectations for sparticle

masses within this rather restricted framework which is completely determined by just four SUSY parameters renormalized at some ultra-high scale where the physics, because of assumptions about the symmetries of the interactions, is simple. These may be taken to be,

- m_0 , a common scalar mass term,
- $m_{1/2}$, a common gaugino mass term,
- A_0 , a common tri-linear coupling, and
- B_0 , a bilinear coupling.

The various gauge and Yukawa couplings and soft breaking terms are then evolved from the unification scale down to the weak scale. The evolution [22] can be traced via 26 renormalization group equations (RGE's). A remarkable consequence of this mechanism is that electroweak symmetry is automatically broken when one of the Higgs mass squared terms gets driven to a negative value. The correct symmetry breaking pattern is then obtained for a large range of model parameters. The bilinear coupling B_0 can be eliminated in favor of $\tan\beta$ (ratio of Higgs field vev's), and the magnitude (but not the sign) of the supersymmetric Higgs mass term μ can be solved for in terms of M_Z . Hence, the complete weak scale sparticle spectrum and sparticle mixing angles can be calculated in terms of the parameter set

$$m_0, m_{1/2}, A_0, \tan\beta, \quad (1.1)$$

together with the sign of μ and the top quark mass m_t . An iterative solution of the RGE's, using two-loop gauge coupling RGE's and the one-loop effective potential, has been implemented as the subprogram ISASUGRA [23], and is a part of the ISAJET package [24], which we use in our analysis.

In order to assess the best channels for SUSY discovery, we first present total cross sections for various sparticle pair-production mechanisms in Fig. 1, for $p\bar{p}$ collisions at $\sqrt{s} = 2$ TeV, using CTEQ2L parton distribution functions [25]. To be specific, we show results for $\tan\beta = 2$ and a large and negative μ value, typical in SUGRA models. For Fig. 1a, we show total cross sections versus $m_{\tilde{g}}$ for $m_{\tilde{g}} = m_{\tilde{q}}$. We see that for $m_{\tilde{g}} < 300$ GeV, strong production of $\tilde{g}\tilde{g}$, $\tilde{g}\tilde{q}$ and $\tilde{q}\tilde{q}$ pairs dominates. However, as $m_{\tilde{g}}$ increases, the strong production cross sections drop steeply, and are ultimately overtaken by those for the production of lighter charginos and neutralinos via the $p\bar{p} \rightarrow \widetilde{W}_1\widetilde{Z}_2$ and $p\bar{p} \rightarrow \widetilde{W}_1\widetilde{W}_1$ reactions. These processes dominate for $m_{\tilde{g}} > 300$ GeV. Also shown is the total cross section [26] for gluinos and squarks produced in association with charginos and neutralinos (labelled assoc. prod.); this class of reactions is always sub-dominant below strongly interacting pair production or chargino/neutralino pair production. In Fig. 1b, we plot the same cross sections, except that now $m_{\tilde{q}} = 2m_{\tilde{g}}$. Again, strongly interacting sparticle pair production (along with on-shell $W \rightarrow \widetilde{W}_1\widetilde{Z}_1$ production) is dominant for small $m_{\tilde{g}}$, but this time it becomes sub-dominant for $m_{\tilde{g}} > 200$ GeV.

The cross sections for a large, positive value of μ are shown in Fig. 2. In this case, \widetilde{W}_1 and $\widetilde{Z}_{1,2}$ tend to be significantly lighter than for negative values of μ , so that their production

cross sections are even larger and dominate the strong production cross sections for smaller gluino masses than in Fig. 1. Notice that, for $\mu > 0$, the non-observation of any SUSY signals at LEP already indirectly excludes gluinos up to about 250 GeV.

The implications from Figs. 1 and 2 are clear: for current values of integrated luminosities, when the Tevatron is exploring $m_{\tilde{g}} < 200 - 300$ GeV, experiments should obtain maximal reach by looking for signals from strongly interacting $\tilde{g}\tilde{g}$, $\tilde{g}\tilde{q}$ and $\tilde{q}\tilde{q}$ production, such as multi-jets + E_T events, and isolated leptons produced *in association* with jets from cascade decays of gluinos and squarks [7]. To probe values of $m_{\tilde{g}} \gtrsim 300$ GeV, which should be possible with larger data samples, Tevatron experiments should focus on signatures from $\widetilde{W}_1\widetilde{Z}_2$ and $\widetilde{W}_1\overline{\widetilde{W}_1}$ production [27]. These reactions will also determine the ultimate reach of experiments at the Tevatron, provided that the decay patterns of the charginos and neutralinos lead to final states that are observable above SM backgrounds. There are only a few promising experimental signatures from $\widetilde{W}_1\widetilde{Z}_2$ and $\widetilde{W}_1\overline{\widetilde{W}_1}$ production. The previously mentioned clean trilepton signal from $\widetilde{W}_1\widetilde{Z}_2 \rightarrow 3\ell + E_T$ occurs at an observable rate in large regions of the SUGRA parameter space and has only tiny *physics* backgrounds. There are also clean isolated dilepton signatures from $\widetilde{W}_1\overline{\widetilde{W}_1} \rightarrow \ell\bar{\ell}' + E_T$ production, although this suffers from large SM background due to WW production. Furthermore, there is an isolated dilepton + jets signature from $\widetilde{W}_1\widetilde{Z}_2 \rightarrow q\bar{q}'\widetilde{Z}_1 + \ell\bar{\ell}\widetilde{Z}_1$, which should be large in much the same region where the 3ℓ signature is visible, but which also suffers from large backgrounds. These dilepton signals could serve to confirm a signal in the relatively clean trilepton channel [28]. Finally, single isolated lepton + jets and multi-jet + E_T signatures from these reactions, and also from $\widetilde{W}_1\widetilde{Z}_1$ production, should be buried below backgrounds from direct W production and QCD multi-jet production, respectively.

To outline the rest of this paper, in Sec. II we show the results of detailed and extensive calculations of signal and background for the $3\ell + E_T$ events, and plot the reach of the Tevatron MI and also TeV* in SUGRA parameter space. In Sec. III, we perform a similar analysis for $\widetilde{W}_1\overline{\widetilde{W}_1} \rightarrow \ell\bar{\ell} + E_T$ events, and in Sec. IV, we consider $\widetilde{W}_1\widetilde{Z}_2 \rightarrow \text{jets} + \ell\bar{\ell} + E_T$ events. In Sec. V, we combine the results of the previous three sections with studies of signals from gluino and squark cascade decays, to compare the SUSY search capabilities of the Main Injector and TeV* upgrades with one another, and also with LEP II and the LHC.

II. REACH VIA THE CLEAN TRILEPTON SIGNAL

To calculate $3\ell + E_T$ signal levels, we use the ISAJET 7.13 event generator program [24]. We generate all possible subprocesses for chargino and neutralino pair production in our calculations, even though $q\bar{q} \rightarrow \widetilde{W}_1\widetilde{Z}_2$ is the dominant component. The various chargino and neutralino decay branching ratios are calculated within ISAJET, to lowest order. ISAJET neglects initial/final state spin correlations, but these are not expected to be of great significance at hadron colliders. ISAJET also neglects decay matrix elements in the event generation (but not the branching fraction calculation); these are mainly expected to be significant when virtual states in 3-body decays are getting close to being on mass shell. ISAJET is also used to calculate the dominant physics backgrounds, which are expected (after cuts) to be $t\bar{t}$ production, and WZ production.

We model experimental conditions using a toy calorimeter with segmentation $\Delta\eta \times \Delta\phi =$

0.1×0.09 and extending to $|\eta| = 4$. We assume an energy resolution of $\frac{0.7}{\sqrt{E}} \left(\frac{0.15}{\sqrt{E}}\right)$ for the hadronic (electromagnetic) calorimeter. Jets are defined to be hadron clusters with $E_T > 15$ GeV in a cone with $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.7$. Leptons with $p_T > 8$ GeV and within $|\eta_\ell| < 3$ are considered to be isolated if the hadronic scalar E_T in a cone with $\Delta R = 0.4$ about the lepton is smaller than $\frac{E_T(\ell)}{4}$. In our analyses, we neglect multiple scattering effects, an explicit detector simulation, and fake backgrounds from γ and jet mis-identification. For this reason, our results should be regarded as optimistic.

To extract signal from background, various sets of cuts have been proposed [13,15,18,19]. In this paper, since we are interested in the maximal reach of a high luminosity Tevatron collider, we take somewhat harder cuts than these previous studies. In Table I, we list the cross section after successive cuts, for two SUGRA cases: $(m_0, m_{1/2}, A_0, \tan\beta, \text{sign}(\mu), m_t) = (200, 165, 0, 2, -1, 170)$ and $(200, 200, 0, 2, +1, 170)$, where all mass parameters are in GeV. We also list backgrounds from $t\bar{t}$ production for $m_t = 170$ GeV, and from WZ production.

The cuts we implement are the following.

- We require 3 *isolated* leptons in each event, with $p_T(\ell_1) > 20$ GeV, $p_T(\ell_2) > 15$ GeV, and $p_T(\ell_3) > 10$ GeV. In addition, each lepton is central ($|\eta| < 2.5$). This cut is labelled (3ℓ) . We see that already the background from $t\bar{t}$ production falls below the 1 fb level, leaving a large WZ background.
- We require $\cancel{E}_T > 25$ GeV (labelled (\cancel{E}_T)). This cut removes backgrounds (not listed) from SM processes such as Drell-Yan dilepton production, where an extra accompanying jet fakes a lepton.
- To reduce background from WZ production, we require that the invariant mass of any opposite-sign, same flavor dilepton pair not reconstruct the Z mass, *i.e.* we require that $|m(\ell\bar{\ell}) - M_Z| \geq 10$ GeV. This cut reduces WZ background to below the 1 fb level, and is labelled (M_Z) .
- We finally require the events to be *clean*, *i.e.* no jets (as defined above) should be present. This is labelled as $(0j)$.

At this point, the surviving total background rates are $\sim 0.2 fb$, leaving ~ 5 background events per $25 fb^{-1}$ of integrated luminosity. The background mainly comes from WZ events, where $Z \rightarrow \tau\bar{\tau}$, with subsequent τ leptonic decay. The 5σ level for discovery of a signal corresponds to $0.45 fb$, or 11 events for the same luminosity. The two signal cases listed in the table are well above this limit.

Our next task is to delineate the regions of SUGRA parameter space where a clean trilepton signal is observable, both for the Tevatron MI, as well as for TeV*, after our simulation of signal events, with the effect of cuts included. We show in Fig. 3a the regions of interest in the m_0 vs. $m_{1/2}$ plane, taking $A_0 = 0$, $\tan\beta = 2$, and $\mu < 0$. Varying A_0 mainly affects third generation sparticle masses, and so has little effect on our results, unless \tilde{t}_1 , \tilde{b}_1 or $\tilde{\tau}_1$ are driven to such low values that new two-body decay modes of charginos and neutralinos open up. We take $m_t = 170$ GeV, consistent with the values recently obtained by the CDF and D0 experiments [29]. The regions of the plane shaded by a brick wall are excluded on theoretical grounds, either because of lack of appropriate electroweak symmetry breaking, or because the LSP becomes either the sneutrino (excluded in Ref. [30], under the

assumption that the LSP constitutes the galactic dark matter), or is charged (usually the \widetilde{W}_1 , \tilde{e}_R or $\tilde{\tau}_1$). The diagonally shaded region is excluded by various experimental constraints, including the LEP limits [4] of $m_{H_\ell} \gtrsim 60$ GeV, $m_{\widetilde{W}_1} > 47$ GeV, and $m_{\tilde{\nu}} > 43$ GeV, and the CDF and D0 limits on $m_{\tilde{g}}$ and $m_{\tilde{q}}$ from multi-jet+ E_T searches [5].

The sampled points in SUGRA space which yield an observable signal at the Tevatron MI, assuming 1 fb^{-1} of integrated luminosity, are shown with black squares. At the MI, where the probability of getting more than one background event is smaller than 2%, we have required a minimum of five signal events to claim discovery—the Poisson probability for the *physics* background to fluctuate to this level is 2×10^{-6} .

To obtain our signal cross section, we generate all possible chargino/neutralino production mechanisms. For each point, we typically generate events until either 25 signal events are produced, or a maximum of 50K events are generated, or the signal cross section falls well below the 3σ level.

To facilitate the translation of the points in the SUGRA m_0 vs. $m_{1/2}$ plane into sparticle masses, we show in Fig. 3b various sparticle mass contours for \tilde{g} , \widetilde{W}_1 and $\tilde{\ell}_R$. By comparing Fig. 3a with 3b, we see that the maximal reach in $m_{\tilde{g}}$ at the MI is achieved at $m_{1/2} \sim 160$ GeV, for which $m_{\tilde{g}} \sim 450$ GeV, and $m_{\widetilde{W}_1} \sim 150$ GeV. In this region of relatively low values of m_0 , sleptons are much lighter than squarks, so leptonic branching ratios of \tilde{Z}_2 are enhanced. For larger values of $m_{1/2}$, the $\tilde{Z}_2 - \tilde{Z}_1$ mass difference becomes sufficiently large that the two body decay mode $\tilde{Z}_2 \rightarrow \tilde{Z}_1 H_\ell$ opens up, dominating the \tilde{Z}_2 branching fractions, and spoiling the signal. The onset of this “spoiler mode” is denoted by the correspondingly labelled horizontal contour. If m_0 is sufficiently small, then sleptons and sneutrinos become light enough that $\tilde{Z}_2 \rightarrow \tilde{\ell}_L \ell$, $\tilde{Z}_2 \rightarrow \tilde{\ell}_R \ell$ or $\tilde{Z}_2 \rightarrow \tilde{\nu}_L \nu$ are accessible, and can dominate \tilde{Z}_2 decay modes. Diagonal contours denoting the regions where these modes are accessible are also labelled. We see that as m_0 increases, squarks and sleptons become increasingly heavy. Even so, for large m_0 , the Tevatron MI still has a reach via clean trileptons out to $m_{1/2} \sim 60 - 80$ GeV, corresponding to $m_{\tilde{g}} \sim 215 - 260$ GeV.

The SUGRA points accessible to TeV* are denoted by squares with x’s (10σ level), and open squares (5σ level). Sampled points with signal between 3-5 σ are labelled with triangles, and points with less than a 3σ signal are denoted by x’s. Note that with the 5σ criterion of observability, the signal to background ratio exceeds two. For small m_0 , we see that TeV* has an extraordinary reach out to $m_{1/2} \sim 280$ GeV, corresponding to $m_{\tilde{g}} \sim 700$ GeV! In this region, \tilde{Z}_2 , which is predominantly $SU(2)$ -gaugino, dominantly decays to $\nu \tilde{\nu}_L$ and $\ell \tilde{\ell}_L$, even though $\tilde{Z}_2 \rightarrow \tilde{Z}_1 H_\ell$ is accessible. As m_0 increases, the $\tilde{Z}_2 \rightarrow \ell \tilde{\ell}_L$ decay mode closes, so $\tilde{Z}_2 \rightarrow \nu \tilde{\nu}_L$ is nearly 100%, and is invisible. This is the cause for the region of non-observability that extends to low $m_{1/2}$, to the left of the $\tilde{Z}_2 \rightarrow \nu \tilde{\nu}_L$ contour. As m_0 increases further, the $\tilde{Z}_2 \rightarrow \nu \tilde{\nu}_L$ decay is no longer accessible and \tilde{Z}_2 decays to $\ell \tilde{\ell}_R$, although this mode now competes with the Higgs spoiler, which is typically larger. For even larger values of m_0 , all two-body decays to sleptons are closed. In this region, TeV* can see (almost) up to the Higgs spoiler over a large range of parameter space, corresponding to $m_{1/2} \sim 170$ GeV, or $m_{\tilde{g}} \sim 500$ GeV, thus considerably expanding upon the reach of the Tevatron MI.

We also see in Fig. 3b the region below the dashed contours which is the approximate reach of LEP II via Higgs, slepton pair or chargino pair searches. We see that the MI and TeV* can probe significant regions beyond the LEP II reach for charginos or sleptons, especially in the small m_0 area. However, if MI or TeV* do see a signal, then LEP II probably

should have discovered the lightest SUSY Higgs boson.

In Fig. 4, we show the same results in the m_0 vs. $m_{1/2}$ plane, except now we choose $\mu > 0$. This mainly alters the masses and mixing angles of the charginos and neutralinos from those in Fig. 3. In this case, we see that the Tevatron MI will have a maximal reach to $m_{1/2} \sim 230$ GeV, corresponding to $m_{\tilde{g}} \sim 600$ GeV, but only in the region where $m_0 \lesssim 150$ GeV. The TeV* option can again greatly expand this region, now probing up to $m_{1/2} \sim 280$ GeV ($m_{\tilde{g}} \sim 740$ GeV) in the favourable case when \tilde{Z}_2 decays to real sleptons are allowed. If these decays are not allowed, then the region of detectability is limited by the opening up of the $\tilde{Z}_2 \rightarrow Z\tilde{Z}_1$ spoiler mode for the lower range of m_0 . Experiments at TeV* can probe m_0 out to $m_0 \sim 300 - 350$ GeV, corresponding to $m_{\tilde{\ell}_R} \lesssim 400$ GeV. There is a major difference between the positive (Fig. 4) and negative (Fig. 3) μ cases: for larger values of m_0 , there is *no reach at all in $m_{1/2}$ beyond current LEP limits*, for $\mu > 0$. This lack of reach can be traced directly to the $\tilde{Z}_2 \rightarrow \ell\bar{\ell}\tilde{Z}_1$ branching fraction, which can drop by two orders of magnitude when the sign of μ is flipped to be positive, in the large m_0 region [31]. The major decrease in \tilde{Z}_2 branching fraction, noted previously in Ref. [13], is mainly due to interference effects amongst the $\tilde{\ell}_L$ and Z mediated three body decay amplitudes. This “hole” lies in the region favored by the simplest $SU(5)$ supergravity GUT model, if we take proton decay and dark matter constraints [32] literally. Such a scenario can thus be well-tested at TeV* (via trileptons) for $\mu < 0$, but not for $\mu > 0$. Finally, we remark that for very large values of m_0 (and correspondingly large slepton and squark masses) the amplitudes for sfermion mediated decays of \tilde{Z}_2 become very small, and the leptonic branching fraction becomes the same as that for the Z boson. The on-set of this effect can be seen in Fig. 4 where we see that for $m_0 \gtrsim 800$ GeV, the crosses give way to triangles and squares indicating the expected reduction of the interference effects.

In Fig. 5, we show again the m_0 vs. $m_{1/2}$ plane, but this time for $\tan\beta = 10$. We only show results for $\mu < 0$ for brevity. For positive values of μ and large values of m_0 very similar results are obtained. This is because for large values of $\tan\beta$ the leptonic branching fraction of \tilde{Z}_2 is roughly symmetric about $\mu = 0$ when its three body decays dominate [13] and the kinematics is roughly similar. For small values of m_0 the results for positive and negative values of μ are somewhat different. For $\mu < 0$ the neutralino mainly decays invisibly via the $\tilde{\nu}\nu$ mode whereas for positive values of μ the $\tilde{\ell}_R\ell$ mode frequently dominates.

From Fig. 5, we see that there are very few points accessible to Tevatron MI. For large values of m_0 , this is mainly due to a large enhancement in the hadronic \tilde{Z}_2 decays, at the expense of leptonic modes. In the small m_0 region, where dominantly two body decays take place, most of the branching fraction is taken up by $\tilde{Z}_2 \rightarrow \tilde{\nu}\nu$ decays. Although the branching fractions to the visible leptonic decays are a few percent, it should be kept in mind that $m_{\tilde{W}_1} - m_{\tilde{\nu}}$ is rather small, so that the daughter lepton from chargino decay tends to be soft resulting in a reduced detection efficiency for these events. The corresponding region may well be larger for positive values of μ and small m_0 where the branching fraction for the leptonic \tilde{Z}_2 decays are almost an order of magnitude larger. As in Fig. 3 and Fig. 4, the TeV* collider option has a much greater reach throughout parameter space than the Tevatron MI, and can explore up to $m_{\tilde{g}} \sim 700$ GeV, but only for a very narrow range of $m_0 \sim 160$ GeV. For $\mu < 0$ and larger values of $m_0 \sim 300 - 800$ GeV, TeV* can probe to $m_{\tilde{g}} \sim 500$ GeV but the 5σ reach frequently does not extend to where the spoiler decays become accessible. Finally, for $m_0 \sim 180 - 300$ GeV, there is again a “hole” of non-observability extending all

the way down to the current LEP constraint, due again to the $\tilde{Z}_2 \rightarrow \ell\bar{\ell}\tilde{Z}_1$ branching fraction suppression (which also occurs when $\mu > 0$).

III. DILEPTON SIGNAL FROM CHARGINO PAIR PRODUCTION

We see from Fig. 1 that at least for the large values of μ expected in SUGRA models, along with $\sigma(p\bar{p} \rightarrow \tilde{W}_1\tilde{Z}_2X)$, the $p\bar{p} \rightarrow \tilde{W}_1\tilde{W}_1X$ cross section remains large out to large values of $m_{\tilde{g}}$. A signal (with the expected strength) in this channel accompanying the clean trilepton events discussed in Section II would serve as strong evidence for the supersymmetric origin of these events. The best signature for chargino pair production is in the clean, opposite-sign (OS), isolated dilepton channel [10,11,13,14]; single lepton plus jets and multi-jet + \cancel{E}_T signatures should be well below SM backgrounds. Assuming that it is possible to veto $Z \rightarrow \ell\bar{\ell}$ events, the major SM backgrounds to the clean OS dilepton signal consist of Drell-Yan $\ell\bar{\ell}$ production, $\gamma^*, Z \rightarrow \tau\bar{\tau}$ production, $t\bar{t}$ production (where the b jets are soft), and pair production of vector bosons, especially WW production.

Since clean dilepton events can come from a variety of SUSY sources, to evaluate the signal we generate *all* possible SUSY production reactions. We implement the following set of cuts, designed to extract signal from these backgrounds. The results of these successive cuts on two signal cases, and backgrounds, are shown in Table II.

- We require exactly two *isolated* OS (either e or μ) leptons in each event, with $p_T(\ell_1) > 10$ GeV and $p_T(\ell_2) > 7$ GeV, and $|\eta(\ell)| < 2.5$. In addition, we require *no* jets, which effectively reduces most of the $t\bar{t}$ background. These cuts are labelled as $(2\ell, 0j)$.
- We require $\cancel{E}_T > 25$ GeV (labelled (\cancel{E}_T)). This cut removes backgrounds from Drell-Yan dilepton production, and also the bulk of the background from $\gamma^*, Z \rightarrow \tau\bar{\tau}$ decay. Notice that the $\gamma^*, Z \rightarrow \tau\bar{\tau}$ background still dominates.
- We require $\phi(\ell\bar{\ell}) < 150^\circ$, to further reduce $\gamma^*, Z \rightarrow \tau\bar{\tau}$ (labelled ϕ).
- We require the Z mass cut: invariant mass of any opposite-sign, same flavor dilepton pair not reconstruct the Z mass, *i.e.* $m(\ell\bar{\ell}) \neq M_Z \pm 10$ GeV. This cut is labelled (M_Z) .

We see from the fourth row of Table II that the dominant remaining background comes from WW production. However, the leptons and \cancel{E}_T from two-body W boson decays are considerably harder than those from three body chargino decay to a massive LSP, via $\tilde{W}_1 \rightarrow e\nu_e\tilde{Z}_1$. It has been shown in Ref. [8] that a cut on $B = |\vec{\cancel{E}}_T| + |p_T(\ell_1)| + |p_T(\ell_2)| < 100$ GeV was effective to separate softer top *squark* events from hard top *quark* events; the same works here to gain significant rejection on WW BG with only modest loss of signal, as shown in Fig. 6. (If the decay channel $\tilde{W}_1 \rightarrow \tilde{Z}_1W$ is open, this cut is not effective; we have, however, checked that these cases are very difficult to see above background anyway.) Hence, we further require

- $B = |\vec{\cancel{E}}_T| + |p_T(\ell_1)| + |p_T(\ell_2)| < 100$ GeV, (labelled as (B)).

The final cross sections for two cases of signal and background are shown in the last row of Table II. Assuming an integrated luminosity of $25 fb^{-1}$, both these signal cases should be

observable above background at the 5σ level. For the second case, this corresponds to 214 signal events, as opposed to ~ 1100 BG events- a 20% effect. While this may sound marginal, we note that the bulk of the background, from WW production, can be well-measured and normalized, so that the signal can be looked for as a distortion in, for instance, the low energy end of the distribution in B shown in Fig. 6.

We plot the regions of observability of this signal in the m_0 vs. $m_{1/2}$ SUGRA plane, in the upper frames *a*) of Figs. 7-9 for the same values of parameters as in Figs. 3-5. The hatched and bricked regions are identical to those in Figs. 3-5. The following points are worth noting.

- For the $\tan \beta = 2$, $\mu < 0$ case illustrated in Fig. 7*a*, the region of space explorable via clean dileptons is a subset of the region accessible via clean trileptons. However, for the $\tan \beta = 2$, $\mu > 0$ case shown in Fig 8*a*, the clean dilepton channel offers a reach well into the “hole” region of the trilepton plot Fig. 4*a*.
- There are significant regions of the m_0 vs. $m_{1/2}$ plane where both the trilepton as well as the clean dilepton signal should be observable. As noted above, the simultaneous detection of a signal in both channels at the expected relative rates, and with the correct kinematics, may serve to identify their origin. It is also instructive to note that charginos should also be detectable at LEP II over much of this same region. Although this will obviously be sensitive to the energy at which LEP II becomes operational, it seems likely that the reach of MI and TeV* in the clean dilepton channel will not significantly exceed that of LEP II.

IV. CONFIRMATION IN OS DILEPTON PLUS JETS CHANNEL

If a signal is detected in the $\widetilde{W}_1 \widetilde{Z}_2 \rightarrow 3\ell + \cancel{E}_T$, then as a confirmation, there ought to be as well a signal in the $\widetilde{W}_1 \widetilde{Z}_2 \rightarrow q\bar{q}'\widetilde{Z}_1 + \ell\bar{\ell}\widetilde{Z}_1$ channel. For this reaction, one ought to detect an OS but same flavor dilepton pair with invariant mass bounded by $m_{\widetilde{Z}_2} - m_{\widetilde{Z}_1}$, recoiling against one or two jets, plus moderate \cancel{E}_T . Although the signal rate is expected to exceed that in the trilepton channel, substantial backgrounds from γ^* , $Z \rightarrow \tau\bar{\tau}$, $t\bar{t}$ and vector boson pair production make detection in this channel more difficult.

Nonetheless, it is interesting to identify regions of SUGRA parameter space where the dilepton plus jets channel yields a confirmatory signature. Again, we must generate *all* possible SUSY reactions. The following set of cuts are implemented, and the results tabulated in Table III.

- We require two *isolated* OS (*same* flavor) dileptons, plus at least one detectable jet. As before, the leptons are required to satisfy $p_T(\ell_1) > 10$ GeV and $p_T(\ell_2) > 7$ GeV, and $|\eta(\ell)| < 2.5$. These cuts are labelled as $(2\ell, nj)$.
- Requiring $\cancel{E}_T > 25$ GeV (labelled (\cancel{E}_T)) removes much of the background from γ^* , $Z \rightarrow \tau\bar{\tau}$ decay and also SM Drell-Yan dilepton production.
- We require $m(\ell\bar{\ell}) < 80$ GeV, to remove backgrounds from Z decays, and much of $t\bar{t}$ production. This cut is labelled $(m_{\ell\bar{\ell}})$.

- We require $\phi(\ell\bar{\ell}) < 90^\circ$, to further reduce $Z \rightarrow \tau\bar{\tau}$ (labelled ϕ).
- Finally, to remove much of the remaining $t\bar{t}$ background, we require $p_T(\text{fast jet}) < 50$ GeV (labelled p_T^j), and invariant mass of all reconstructed jets to be $m(\text{jets}) < 70$ GeV (labelled m_{jets}).

The residual backgrounds after these cuts mainly come from vector boson pair production and from $\tau\bar{\tau}$ pair production, and sum to 25.6 fb . For 25 fb^{-1} of integrated luminosity, the signal cross section required for a 5σ observation is 5.1 fb . Both of the signal cases listed in Table III are thus observable. We remark again that the main background processes will be well measured from collider data. In addition, since the signal only occurs in the same-flavor channel, it leads to an excess of $e\bar{e}$ and $\mu\bar{\mu}$ events over $e\bar{\mu} + \bar{e}\mu$ events.

The regions of the SUGRA plane where this signal is observable are shown in Fig. 7b-9b for the same values of parameters as in Figs. 7a-9a. We see that except for tiny regions of parameter space, this signal does not probe regions not accessible via the other channels. There are, however, sizeable regions where the jets plus OS dilepton signal can be used to confirm a signal seen in other channels.

Finally, we remark that a simultaneous measurement of the SUSY cross section in this channel together with $\sigma(3\ell)$ discussed in Sec. II, directly yields the leptonic branching fraction for decays of the chargino. This assumes that the sample of jets plus OS dilepton events comes mainly from $\widetilde{W}_1\widetilde{Z}_2$ production; *i.e.* contributions from other SUSY sources are negligible, and further, that the background can be reliably subtracted. It would thus be interesting to see if cuts can be devised to separate the $\widetilde{W}_1\widetilde{Z}_2$ source of these dilepton events from cascade decays of squarks and gluinos or from associated production processes as was done for the trilepton events in Ref. [33]

V. OTHER SEARCH STRATEGIES AND CONCLUDING REMARKS

A. Summary of signals from charginos and neutralinos

In supersymmetric models where the running gaugino masses unify at a high scale, and the weak scale parameter μ greatly exceeds the $U(1)$ and $SU(2)$ gaugino masses M_1 and M_2 (as is the case for the minimal SUGRA model), one typically expects $m_{\widetilde{W}_1} \sim m_{\widetilde{Z}_2} \sim (\frac{1}{3} - \frac{1}{4})m_{\tilde{g}}$. As a result, $p\bar{p} \rightarrow \widetilde{W}_1\widetilde{Z}_2$ and $p\bar{p} \rightarrow \widetilde{W}_1\overline{\widetilde{W}_1}$ are the dominant sparticle production processes at the Tevatron if gluinos and squarks are heavier than 250-300 GeV, so that signals from these channels offer the best reach for supersymmetry at high luminosity upgrades of the Tevatron. The most promising signals from these reactions are:

- clean (*i.e.* jet-free), isolated trilepton events from $\widetilde{W}_1\widetilde{Z}_2 \rightarrow 3\ell + \not{E}_T$,
- clean, OS dilepton events from $\widetilde{W}_1\overline{\widetilde{W}_1} \rightarrow \ell\ell' + \not{E}_T$, and
- OS but same flavour dilepton plus jets events from $\widetilde{W}_1\widetilde{Z}_2 \rightarrow q\bar{q}'\ell\bar{\ell} + \not{E}_T$.

Motivated by the recent interest in the TeV* upgrade of the Tevatron collider—designed to yield an integrated luminosity of $\sim 25 \text{ fb}^{-1}$ —we have used ISAJET to compute these

SUSY signals within the framework of the minimal supergravity model with gauge coupling unification and radiative breaking of electroweak symmetry. Specifically, we have scanned sections of the multi-dimensional parameter space, and delineated the regions where the SUSY signal is observable over SM *physics* backgrounds. Since we have not included a real detector simulation, effects due to multiple scattering during bunch crossings, or backgrounds due to π 's or γ 's faking an electron (these are all sensitive to details of the ultimate collider and detector design), our conclusions must be regarded as on the optimistic side.

The region of the $m_0 - m_{1/2}$ supergravity parameter plane where the trilepton signal is expected to be observable, with a significance $\geq 5\sigma$ at the Main Injector and at the TeV*, is shown by solid squares and hollow squares, respectively, in Figs. 3-5a. Figs. 7-9 illustrate the corresponding regions where the dilepton signals are expected to be observable. From these figures, we see that experiments at TeV* should be able to probe significantly larger regions of parameter space than at the Main Injector, in both the dilepton and trilepton channels. When m_0 is small (≤ 200 GeV), the trilepton signal may be (indirectly) sensitive to gluino masses as heavy as ~ 700 GeV! However, even in this favorable region, there exist holes of non-observability due to neutralino/chargino decays to soft or invisible particles. For $\tan \beta = 2$, m_0 large (> 400 GeV) and negative values of μ , experiments at TeV* may be able to see trilepton signals essentially until the “spoiler mode” $\tilde{Z}_2 \rightarrow \tilde{Z}_1 H_\ell$ becomes accessible ($m_{\tilde{g}} \sim 500$ GeV). However, if $\mu > 0$, large interference effects in the neutralino leptonic decay width severely suppress the signal if $400 \text{ GeV} \lesssim m_0 \lesssim 1000 \text{ GeV}$, and a gaping hole where there is no detectable trilepton signal remains in the parameter space, all the way down to the currently excluded LEP chargino mass limit. For large values of $\tan \beta$, the parameter space hole is somewhat smaller, though generally speaking the cross section often falls below the detectable level even when the spoiler decay modes of \tilde{Z}_2 are closed.

If a trilepton signal is discovered, will there be a confirming discovery in the dilepton channels? Are clean dilepton signals observable in the parameter space hole mentioned above? Figs. 7-9 show that indeed large regions of parameter space can be probed in the dilepton channel. The region probed by the OS dilepton plus jets channel forms a subset of that explorable via trileptons. However, the clean (no jets) OS dilepton channel is to some extent complementary to the trilepton channel, in that this signal can be seen in regions of parameter space where the trilepton signal is suppressed. We note, however, that the regions explorable via dileptons at TeV* overlap considerably with the regions explorable by LEP II via slepton and chargino searches, as shown by the dashed contours in Figs. 3b-5b.

B. Comparison with signals from other channels

How does the reach for supersymmetry in the OS dilepton and trilepton channels considered here compare with the reach in other channels such as multi-jets + \cancel{E}_T and same-sign dileptons? The various multi-jet and multi-lepton signals from production and cascade decay of all SUSY particles have been computed previously in Ref. [7] for $\mu = -m_{\tilde{g}}$. We have repeated this calculation for comparison with the results obtained here, except now we use the SUGRA parameters with $m_0 = m_{1/2}$ (which yields $m_{\tilde{q}} \sim m_{\tilde{g}}$) and $m_0 = 4m_{1/2}$ (which yields $m_{\tilde{q}} \sim (1.5 - 1.7)m_{\tilde{g}}$, and consider both signs of μ . We set $A_0 = 0$, and $\tan \beta = 2$. We have computed the cross sections for the multi-jet + \cancel{E}_T and SS dilepton event topologies, with the same cuts as in Ref. [7] for various values of $m_{1/2}$ ($\sim \frac{1}{3}m_{\tilde{g}}$) and compared against

SM backgrounds [7] for $m_t = 170$ GeV. The reach of the Tevatron MI, and also TeV^* , computed in terms of $m_{\tilde{g}}$, is shown in Table IV, for comparison with results obtained in this paper. The reader should view these numbers in proper perspective, since we have not scanned the complete parameter space in constructing this Table, but have fixed A_0 and $\tan \beta$. Indeed, the reach in some channels, *e.g.* the trilepton channel, is sensitive especially to $\tan \beta$.

For the multi-jet + E_T channel (labelled E_T), naive application of the 5σ criterion gives a reach of typically 350-400 GeV at the TeV^* (listed in parenthesis). However, since the signal to background ratio $\frac{S}{B}$ is smaller than 3% (if the signal is at the 5σ level), and there are no characteristic kinematic bumps expected in the signal, it may not be realistic to expect detectability at this level. We, therefore, also list a conservative reach by requiring, in addition, $\frac{S}{B} > 0.25$ (no parenthesis).

The most peculiar point about the E_T signal is that in the trilepton “hole” region, for the MI at least, there is again no reach beyond the current LEP chargino bound. This is because for $\mu > 0$ and small values of $\tan \beta$, the LEP chargino limit already implies $m_{\tilde{g}} \gtrsim 250$ GeV, for which the strong production cross sections are already rather small [34]. As can be seen from Fig. 2b, chargino/neutralino pair production is the dominant production mechanism, and most multi-jet + E_T events come from their hadronic decays. Since \widetilde{W}_1 and $\widetilde{Z}_{1,2}$ tend to be especially light for positive values of μ , their production yields a rather soft E_T spectrum, which is difficult to see above background.

We also list the reach for supersymmetry in the SS dilepton channel. This signal was originally proposed as a way to test the Majorana nature of the gluino, by searching for $\tilde{g} \rightarrow q\bar{q}\widetilde{W}_1$ decays, followed by $\widetilde{W}_1 \rightarrow \ell\nu\widetilde{Z}_1$. The $\tilde{g}\tilde{g} \rightarrow \ell^\pm\ell^\pm + \text{jets} + E_T$ channel is of course only useful as long as one is making a sufficient number of gluino pairs in the first place, and that there is a reasonable efficiency to detect the decay leptons. We see from Table IV that the SS dilepton signal is as well not visible in the trilepton “hole” region, due to a combination of low production cross section together with a low efficiency to detect the leptons which tend to be soft because both $m_{\widetilde{W}_1}$ and $m_{\widetilde{W}_1} - m_{\widetilde{Z}_1}$ tend to be smaller for $\mu > 0$ as compared to for $\mu < 0$. Indeed, for the other parameters of Table IV where there is a reach via SS dileptons up to quite high values of $m_{\tilde{g}}$, most of the dileptons originate from 3ℓ events, where one of the leptons is lost. We further see from Table IV that the reach in SS or OS dileptons is generally similar, and that in moving from Tevatron MI to TeV^* , the reach in $m_{\tilde{g}}$ is increased by typically 100 GeV.

Slepton pair production (which has been included in our computation) is best detected via the clean OS lepton signal [35]. The slepton signal will be observable at the MI only for slepton masses lighter than around 50 GeV [35], while the reach of TeV^* is comparable to that of LEP II.

A comparison of the reach of every channel shows that the maximal reach is always obtained in the clean 3ℓ channel, except for the “hole” region where $m_0 \gtrsim 400$ GeV, and $\mu > 0$: in this region, only TeV^* has a significant reach in the clean OS dilepton channel, and perhaps, in the E_T channel.

C. Conclusions

The current run of the Tevatron $p\bar{p}$ collider, run IB, is expected to attain 0.1 fb^{-1} of integrated luminosity per experiment. With such a data sample, the CDF and D0 experiments should be sensitive to SUSY signals in several channels other than the canonical multi-jet + E_T channel. In particular, the clean trilepton channel ought to allow Tevatron experiments to probe regions of parameter space significantly beyond the range of LEP, and perhaps, even up to the reach of LEP II.

In 1996, LEP II is expected to ramp up to CM energy $\sqrt{s} \sim 175 - 190 \text{ GeV}$, which should allow $m_{\tilde{\ell}}$, $m_{\tilde{W}_1}$ and $m_{H_\ell} \sim 80 - 90 \text{ GeV}$ to be probed. The relatively model-independent search for supersymmetry will optimistically probe the regions below the dashed contours in Figs. 3b-5b. By 1999, the Tevatron MI may be operational, and is expected to amass $\sim 1 \text{ fb}^{-1}$ of data per experiment. The regions explorable at the MI can be significantly larger than those accessible to LEP II, but only in the lower regions of m_0 , where sleptons are significantly lighter than squarks, so that leptonic decays of neutralinos are enhanced. The reach of the Tevatron MI via dilepton signals is essentially a subset of the parameter space that LEP II can explore, so we do not expect new progress to be made in this channel by MI experiments, above and beyond what LEP II can do.

An upgrade of the Tevatron to TeV^* would be particularly well-suited to exploit the clean trilepton channel expected from many SUSY models. The relatively small signal rates may well be detectable above tiny SM backgrounds, if machine and detector dependent backgrounds can be controlled. A luminosity upgrade to $\sim 25 \text{ fb}^{-1}$ of integrated luminosity ought to allow for a substantial increase in the amount of SUSY parameter space that can be explored: in favourable cases, equivalent gluino masses as high as 700 GeV can be probed! However, in spite of its increased reach for SUSY, we note that there are substantial regions of SUSY parameter space which *cannot* be explored by TeV^* , either due to invisible neutralino decays, leptonic branching fraction suppression, the turn on of neutralino spoiler modes, or just kinematically suppressed production cross sections.

Probably the main motivation for weak scale supersymmetry comes from the fact that it provides a mechanism for stabilizing the weak scale if sparticle masses are smaller than $\sim 1 \text{ TeV}$. Some authors have attempted to quantify this by imposing fine-tuning requirements, and have obtained upper bounds on sparticle masses [36]. Their arguments, although admittedly rather subjective, nonetheless suggest sparticle mass bounds $m_{\tilde{g}}, m_{\tilde{q}} \lesssim 700 - 800 \text{ GeV}$. Even taking such an upper limit literally, it would still not be possible to make a definitive search for supersymmetry at LEP II or at TeV^* . On the other hand, recent work [37,38] on the multi-jet + E_T signal indicates that the CERN LHC pp collider, operating at $\sqrt{s} = 14 \text{ TeV}$, can explore the entire range of parameter space up to $m_{\tilde{g}} \sim 1300 \text{ GeV}$ ($m_{\tilde{q}} >> m_{\tilde{g}}$) or $m_{\tilde{g}} \sim 2000 \text{ GeV}$ ($m_{\tilde{q}} \sim m_{\tilde{g}}$). It thus appears that experiments at supercolliders are essential to ensure that weak scale SUSY does not escape experimental detection.

ACKNOWLEDGMENTS

We thank Kaushik De, Teruki Kamon, and the Fermilab TeV^* working group for motivating this project. We thank A. Bartl, and also M. Brhlik, for independently confirming

our branching fraction calculations. This research was supported in part by the U. S. DOE grants DE-FG-05-87ER40319, DE-FG-03-94ER40833, and DE-FG-02-91ER40685.

REFERENCES

- [1] For phenomenological reviews of SUSY, see H. P. Nilles, Phys. Rep. **110**, 1 (1984); H. Haber and G. Kane, Phys. Rep. **117**, 75 (1985); X. Tata, in *The Standard Model and Beyond*, p. 304, edited by J. E. Kim, World Scientific (1991); R. Arnowitt and P. Nath, *Lectures presented at the VII J. A. Swieca Summer School, Campos do Jordao, Brazil, 1993* CTP-TAMU-52/93; *Properties of SUSY Particles*, L. Cifarelli and V. Khoze, Editors, World Scientific (1993).
- [2] See H. Baer *et. al.*, in *Electroweak Symmetry Breaking and Beyond the Standard Model*, edited by T. Barklow, S. Dawson, H. Haber and J. Siegrist, (World Scientific, 1995), FSU-HEP-950401.
- [3] U. Amaldi, W. de Boer and H. Fürstenau, Phys. Lett. **B260**, 447 (1991); J. Ellis, S. Kelley and D. Nanopoulos, Phys. Lett. **B260**, 131 (1991); P. Langacker and M. Luo, Phys. Rev. **D44**, 817 (1991).
- [4] D. Decamp *et.al.* (ALEPH Collaboration), Phys. Rep. **216**, 253 (1992); P. Abreu *et.al.* (DELPHI Collaboration), Phys. Lett. **B247**, 157 (1990); O. Adriani *et.al.* (L3 Collaboration), Phys. Rep. **236**, 1 (1993); M. Akrawy *et.al.* (OPAL Collaboration), Phys. Lett. **B240**, 261 (1990); for a review, see G. Giacomelli and P. Giacomelli, Riv. Nuovo Cim. **16**, 1 (1993).
- [5] M. Paterno, Ph.D. thesis; D. Claes (D0 Collaboration), *presented at the 8th DPF meeting, Albuquerque, NM, Aug. 1994*; F. Abe *et. al.*, (CDF Collaboration), Phys. Rev. Lett. **69**, 3439 (1992).
- [6] C. Dionisi *et. al.* in Proceedings of the ECFA Workshop on LEP 200, A. Böhm and W. Hoogland, Editors, CERN Report, 87-08 (1987); M. Chen *et. al.* Phys. Rep. **159**, 201 (1988).
- [7] H. Baer, C. Kao and X. Tata, Phys. Rev. **D48**, R2978 (1993) and Phys. Rev. **D51**, 2180 (1995).
- [8] H. Baer, M. Drees, R. Godbole, J. Gunion and X. Tata, Phys. Rev. **D44**, 725 (1991); H. Baer, J. Sender and X. Tata, Phys. Rev. **D50**, 4517 (1994).
- [9] J. Ellis and S. Rudaz, Phys. Lett. **B128**, 248 (1983).
- [10] D. Dicus, S. Nandi and X. Tata, Phys. Lett. **B129**, 451 (1983); A. Chamseddine, P. Nath and R. Arnowitt, Phys. Lett. **B129**, 445 (1983); H. Baer and X. Tata, Phys. Lett. **B155**, 278 (1985); H. Baer, K. Hagiwara and X. Tata, Phys. Rev. Lett. **57**, 294 (1986) and Phys. Rev. **D35**, 1598 (1987).
- [11] R. Arnowitt and P. Nath, Mod. Phys. Lett. **A2**, 331 (1987).
- [12] R. Barbieri, F. Caravaglios, M. Frigeni and M. Mangano, Nucl. Phys. **B367**, 28 (1993).
- [13] H. Baer and X. Tata, Phys. Rev. **D47**, 2739 (1993); H. Baer, C. Kao and X. Tata, Phys. Rev. **D48**, 5175 (1993).
- [14] J. Lopez, D. Nanopoulos, X. Wang and A. Zichichi, Phys. Rev. **D48**, 2062 (1993) and CERN-TH.7535/94; J. Lopez, D. Nanopoulos, G. Park, X. Wang and A. Zichichi, Phys. Rev. **D50**, 2164 (1994).
- [15] T. Kamon, J. Lopez, P. McIntyre and J. T. White, Phys. Rev. **D50**, 5676 (1994).
- [16] J. Wells, in *SUSY 94*, p. 553, edited by C. Kolda and J. Wells (U. of Michigan press UM-TH-94-35), 1994; see also talks by G. Kane at *Workshop on Future Facilities at FNAL*, Ann Arbor, October 1994 and talk at *Beyond the Standard Model IV* meeting, Lake Tahoe, 1994.

- [17] H. Baer, J. Gunion, C. Kao and H. Pois, Phys. Rev. **D51**, 2159 (1995).
- [18] F. Abe, *et. al.*, (CDF Collaboration), Fermilab-Conf-93/213-E (1993), submitted to 16th International Symposium on Lepton and Photon Interactions, Ithaca, NY, 10-15 Aug 1993.
- [19] See talk by L. Sawyer (D0 Collaboration), in Proceedings of International Workshop on Supersymmetry and Unification of Fundamental Interactions (SUSY 94), ed. by C. Kolda and J. Wells (U. of Michigan, 1994).
- [20] See *e.g.* R. Arnowitt and P. Nath, Ref. [1]
- [21] Some recent analyses of supergravity mass patterns include, G. Ross and R. G. Roberts, Nucl. Phys. **B377**, 571 (1992); R. Arnowitt and P. Nath, Phys. Rev. Lett. **69**, 725 (1992); M. Drees and M. M. Nojiri, Nucl. Phys. **B369**, 54 (1993); S. Kelley, J. Lopez, D. Nanopoulos, H. Pois and K. Yuan, Nucl. Phys. **B398**, 3 (1993); M. Olechowski and S. Pokorski, Nucl. Phys. **B404**, 590 (1993); V. Barger, M. Berger and P. Ohmann, *ibid.* **49**, 4908 (1994); G. Kane, C. Kolda, L. Roszkowski and J. Wells, Phys. Rev. **D49**, 6173 (1994); D. J. Castaño, E. Piard and P. Ramond, Phys. Rev. **D49**, 4882 (1994); W. de Boer, R. Ehret and D. Kazakov, Karlsruhe preprint, IEKP-KA/94-05 (1994); H. Baer, C. H. Chen, R. Munroe, F. Paige and X. Tata, Phys. Rev. **D51**, 1046 (1995).
- [22] K. Inoue, A. Kakuto, H. Komatsu and H. Takeshita, Prog. Theor. Phys. **68**, 927 (1982) and **71**, 413 (1984).
- [23] See H. Baer *et. al.*, Ref. [21].
- [24] F. Paige and S. Protopopescu, in *Supercollider Physics*, p. 41, ed. D. Soper (World Scientific, 1986); H. Baer, F. Paige, S. Protopopescu and X. Tata, in *Proceedings of the Workshop on Physics at Current Accelerators and the Supercollider*, ed. J. Hewett, A. White and D. Zeppenfeld, (Argonne National Laboratory pub. ANL-HEP-CP-93-92, 1993).
- [25] J. Botts *et. al.*, Phys. Lett. **B304**, 159 (1993).
- [26] H. Baer, D. Karatas and X. Tata, Phys. Rev. **D42**, 2259 (1990).
- [27] Other reactions, such as $\tilde{Z}_1\tilde{Z}_2$ and $\tilde{Z}_2\tilde{Z}_2$ production, occur at much smaller rates when $|\mu|$ is large, as in minimal SUGRA models.
- [28] In addition there may be an observable rate for clean like-sign dilepton events from $\tilde{W}_1\tilde{Z}_2$ when one of the three leptons escapes detection. This signal cannot, however, be used as a confirmatory channel since it has exactly the same origin as the trilepton signal. It would not be unreasonable to add this cross section to the trilepton cross section in evaluating the reach of the TeV* since both these channels are free of physics backgrounds. We have conservatively not done so in our analysis.
- [29] F. Abe *et. al.*, (CDF Collaboration), FERMILAB Pub-95/022-E; S. Abachi *et. al.*, (D0 Collaboration), FERMILAB Pub-95/028-E.
- [30] See *e.g.* H. Baer, M. Drees and X. Tata, Phys. Rev. **D41**, 3414 (1991).
- [31] The result presented here is at variance with results presented in Ref. [14–16], where the authors suggest that trilepton searches will significantly extend the reach in \tilde{W}_1 independently of the sign of μ .
- [32] R. Arnowitt and P. Nath, Phys. Lett. **B299**, 58 (1993) and Phys. Rev. **D49**, 1479 (1994); J. Lopez, D. Nanopoulos and H. Pois, Phys. Rev. **D47**, 2468 (1993).
- [33] H. Baer, C-H. Chen, F. Paige and X. Tata, Phys. Rev. **D50**, 4508 (1994).
- [34] Of course, Tevatron experiments should independently search for gluinos, regardless of

the LEP constraints on the chargino mass since the gaugino mass unification assumption could turn out to be false.

- [35] H. Baer, C-H. Chen, F. Paige and X. Tata, Phys. Rev. **D49**, 3283 (1994).
- [36] R. Barbieri and G. Giudice, Nucl. Phys. **B306**, 63 (1988); see G. Anderson and D. Castano, MIT-CTP-2369 (1994), for an updated measure of fine-tuning, and associated limits on sparticle masses.
- [37] The ATLAS Technical Proposal, CERN/LHCC/94-43 (1994).
- [38] H. Baer, C-H. Chen, F. Paige and X. Tata, Hawaii preprint, UH-511-817-95 (1995).

TABLES

TABLE I. Cross section in fb for the clean trilepton signal before and after successive cuts for two signal cases, and major physics backgrounds. The signal cases list the value of $(m_0, m_{1/2}, \text{sgn}(\mu))$, and take $A_0 = 0$ and $\tan\beta = 2$.

cuts	(200, 165, -1)	(200, 200, +1)	$t\bar{t}(170)$	WZ	<i>total BG</i>
3ℓ	6.3	4.3	0.29	26.9	27.2
$3\ell, \cancel{E}_T$	5.3	4.3	0.26	21.1	21.4
$3\ell, \cancel{E}_T, M_Z$	5.0	3.4	0.2	0.35	0.55
$3\ell, \cancel{E}_T, M_Z, 0j$	2.4	1.7	0.005	0.2	0.205

TABLE II. Cross section in fb for the clean, OS dilepton signal, before and after successive cuts for two signal cases, and major physics backgrounds. The signal cases list the value of $(m_0, m_{1/2}, \text{sgn}(\mu))$, and take $A_0 = 0$ and $\tan\beta = 2$.

cuts	(200, 100, +1)	(600, 80, +1)	$t\bar{t}(170)$	$\gamma^*, Z \rightarrow \tau\bar{\tau}$	WW	WZ	ZZ	<i>total BG</i>
$2\ell, 0j$	130.7	57.5	0.24	10203	211.4	5.1	12.6	10432.3
$2\ell, 0j, \cancel{E}_T$	41.2	13.6	0.2	444.1	150.2	3.2	9.5	607.2
$2\ell, 0j, \cancel{E}_T, \phi$	34.0	9.5	0.15	4.7	126.1	2.4	7.1	140.4
$2\ell, 0j, \cancel{E}_T, \phi, M_Z$	33.9	9.3	0.1	4.7	118.8	0.7	0.1	124.4
$2\ell, 0j, \cancel{E}_T, \phi, M_Z, B$	30.1	8.6	0.02	4.7	38.7	0.3	0.1	43.8

TABLE III. Cross section in fb for the OS same-flavor dilepton plus jets signal, before and after successive cuts for two signal cases, and major physics backgrounds. The signal cases list the value of $(m_0, m_{1/2}, \text{sgn}(\mu))$, and take $A_0 = 0$ and $\tan\beta = 2$. The BG entry VV sums over WW , WZ and ZZ production.

cuts	(200, 150, -1)	(300, 100, +1)	$t\bar{t}(170)$	$\gamma^*, Z \rightarrow \tau\bar{\tau}$	VV	<i>total BG</i>
$2\ell, nj$	32.2	28.3	134	893	264.4	1291.4
$2\ell, nj, \cancel{E}_T$	25.6	12.5	119.6	281	93.1	493.7
$2\ell, nj, \cancel{E}_T, m_{\ell\bar{\ell}}$	25.5	12.5	58.9	281	46.9	386.8
$2\ell, nj, \cancel{E}_T, m_{\ell\bar{\ell}}, \phi$	14.7	8.1	36	48.6	22.3	106.9
$2\ell, nj, \cancel{E}_T, m_{\ell\bar{\ell}}, \phi, p_T^j$	7.8	5.9	4.6	13.1	16.9	34.6
$2\ell, nj, \cancel{E}_T, m_{\ell\bar{\ell}}, \phi, p_T^j, m_{jets}$	6.2	5.2	1.7	9.0	14.9	25.6

TABLE IV. Approximate reach in terms of $m_{\tilde{g}}$ (GeV) via various event topologies for *a*) Tevatron Main Injector and *b*) TeV*, assuming $A_0 = 0$ and $\tan \beta = 2$, with other SUGRA parameters as listed. We use $m_t = 170$ GeV for the background. None means that there is no reach beyond the current LEP bound.

case	\not{E}_T	$OS(0j)$	$OS(nj)$	SS	3ℓ
<i>a) MI</i> ($1fb^{-1}$)					
$m_0 \sim m_{1/2}$ ($\mu < 0$)	310 (330)	275	330	330	450
$m_0 \sim m_{1/2}$ ($\mu > 0$)	320 (345)	400	360	370	600
$m_0 \sim 4m_{1/2}$ ($\mu < 0$)	230 (260)	180	270	270	310
$m_0 \sim 4m_{1/2}$ ($\mu > 0$)	none (none)	none	none	none	none
<i>b) TeV*</i> ($25fb^{-1}$)					
$m_0 \sim m_{1/2}$ ($\mu < 0$)	310 (400)	380	440	430	700
$m_0 \sim m_{1/2}$ ($\mu > 0$)	320 (430)	500	490	480	700
$m_0 \sim 4m_{1/2}$ ($\mu < 0$)	230 (345)	300	360	370	500
$m_0 \sim 4m_{1/2}$ ($\mu > 0$)	none (365)	300	none	none	none

FIGURES

FIG. 1. Cross sections at the Tevatron ($\sqrt{s} = 2$ TeV) for total $\tilde{g}\tilde{g} + \tilde{g}\tilde{q} + \tilde{q}\tilde{q}$ production, associated production, and $\widetilde{W}_1\widetilde{Z}_2$ as well as $\widetilde{W}_1\overline{\widetilde{W}_1}$ and $\widetilde{W}_1\widetilde{Z}_1$ production, as a function of $m_{\tilde{g}}$. In *a*), we take $m_{\tilde{q}} = m_{\tilde{g}}$, while in *b*) we take $m_{\tilde{q}} = 2m_{\tilde{g}}$. We have also taken $\tan \beta = 2$ and $\mu = -m_{\tilde{g}}$.

FIG. 2. Same as Fig. 1, except $\mu = +m_{\tilde{g}}$.

FIG. 3. In *a*), we show regions of the m_0 vs. $m_{1/2}$ plane where supersymmetry should be detectable at the Tevatron MI (black squares), and at TeV^* at 10σ (squares with x) and 5σ levels (empty squares), by searching for clean trilepton events. The bricked region is excluded by theoretical constraints, while the gray shaded region is excluded by experiment. We take $\tan \beta = 2$, $A_0 = 0$, $\mu < 0$, and $m_t = 170$ GeV. In *b*), we show various contours for $m_{\tilde{g}}$, $m_{\widetilde{W}_1}$, and $m_{\tilde{\ell}_R}$ for comparison with the results of *a*). We also show via the dashed contours in *b*) the approximate reach of LEP II.

FIG. 4. Same as Fig. 3, except now $\mu > 0$.

FIG. 5. Same as Fig. 3, except that $\tan \beta = 10$.

FIG. 6. Distribution in $B = |\vec{H}_T| + |p_T(\ell_1)| + |p_T(\ell_2)|$, for WW background (histogram), and the two signal cases of Table 2, after the first four cuts of Table 2.

FIG. 7. In *a*), we show regions of the m_0 vs. $m_{1/2}$ plane where signals should be detectable at the Tevatron MI (black squares), and at TeV^* at 10σ (squares with x) and 5σ levels (empty squares), by searching for clean *dilepton* events. The bricked region is excluded by theoretical constraints, while the gray shaded region is excluded by experiment. We take $\tan \beta = 2$, $A_0 = 0$, $\mu < 0$, and $m_t = 170$ GeV. In *b*), we show similar regions for the *dilepton plus jets* signal.

FIG. 8. Same as Fig. 7, except $\mu > 0$.

FIG. 9. Same as Fig. 7, except $\tan \beta = 10$.

This figure "fig1-1.png" is available in "png" format from:

<http://arXiv.org/ps/hep-ph/9504234v1>

This figure "fig2-1.png" is available in "png" format from:

<http://arXiv.org/ps/hep-ph/9504234v1>

This figure "fig1-2.png" is available in "png" format from:

<http://arXiv.org/ps/hep-ph/9504234v1>

This figure "fig2-2.png" is available in "png" format from:

<http://arXiv.org/ps/hep-ph/9504234v1>

This figure "fig1-3.png" is available in "png" format from:

<http://arXiv.org/ps/hep-ph/9504234v1>

This figure "fig2-3.png" is available in "png" format from:

<http://arXiv.org/ps/hep-ph/9504234v1>

This figure "fig1-4.png" is available in "png" format from:

<http://arXiv.org/ps/hep-ph/9504234v1>

This figure "fig2-4.png" is available in "png" format from:

<http://arXiv.org/ps/hep-ph/9504234v1>

This figure "fig1-5.png" is available in "png" format from:

<http://arXiv.org/ps/hep-ph/9504234v1>